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September 6th 2023

Probing new physics on the horizon of black holes with gravitational waves

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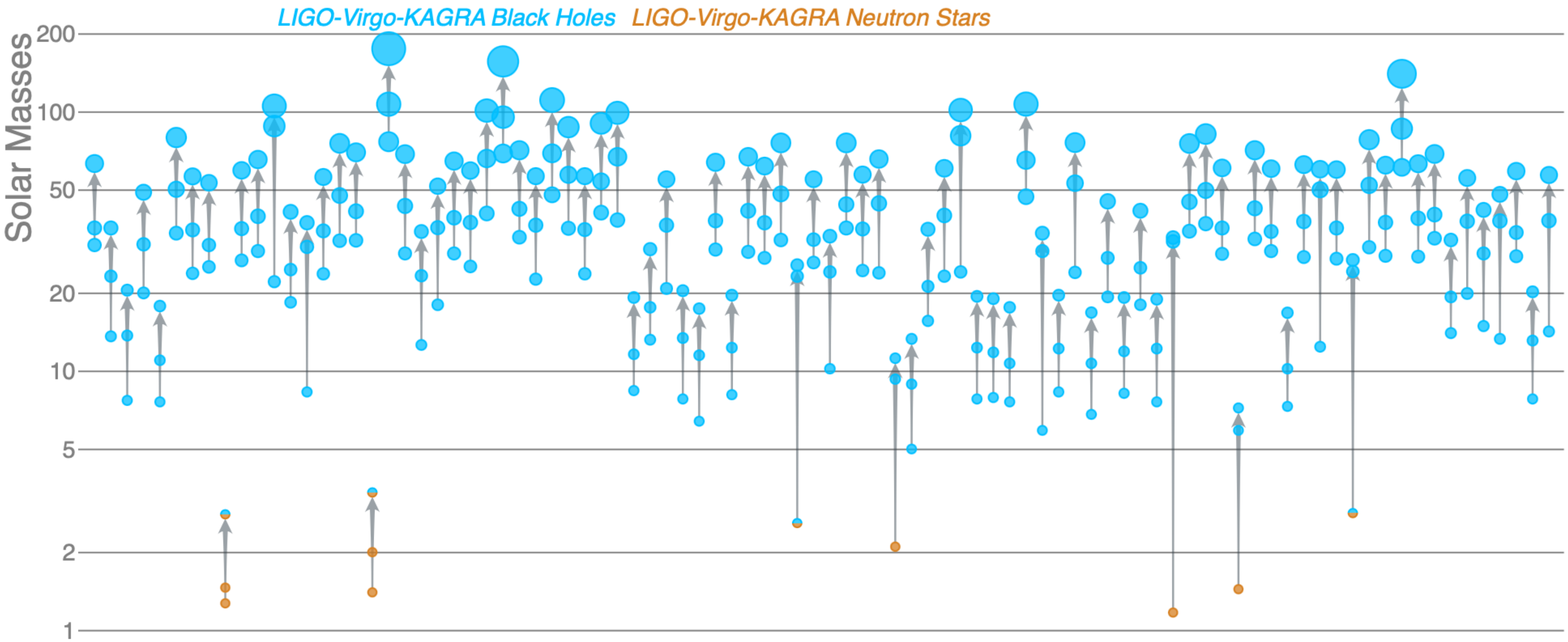
MARIE CURIE ACTIONS

Gravitational-wave detections

The ground-based detectors LIGO and Virgo have detected 90 gravitational-wave events from the coalescence of compact binaries.

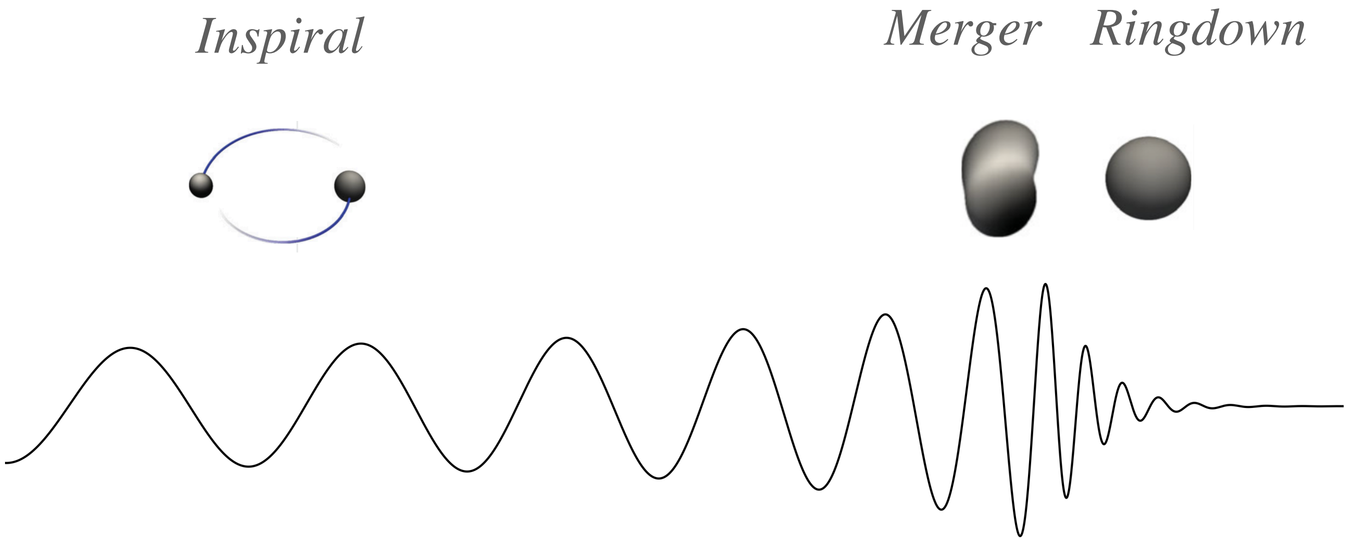


Abbott+, PRX **9**, 031040 (2019); Abbott+, PRX **11**, 021053 (2021); Abbott+, arXiv:2111.03606 (2021)

The O4 observing run started in May 2023 and will last 20 months.

Gravitational waves from binary mergers

The stages of compact binary coalescences are:



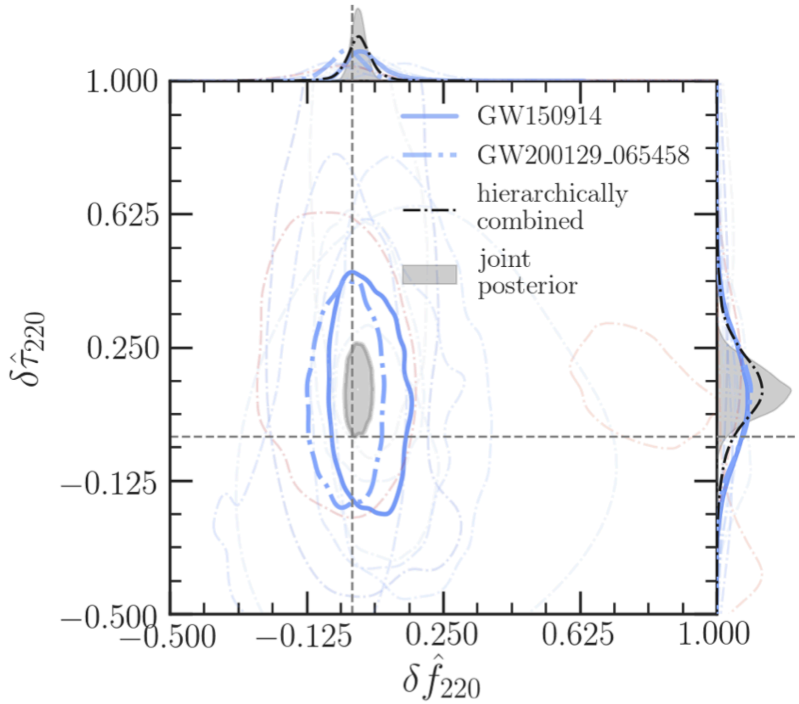
Adapted from Abbott+, PRL **116** n.6 (2016) 061102

Gravitational waves provide a unique channel for probing general relativity.

Abbott+, PRD **100**, 104036 (2019); Abbott+, PRD **103**, 122002 (2021); Abbott+, arXiv: 2112.06861 (2021)

Ringdown tests

The ringdown is modeled as a sum of exponentially dumped sinusoids whose frequencies and damping times are related to the **quasi-normal modes** of the remnant, $\omega = \omega_R + i\omega_I$.



Abbott+, arXiv: 2112.06861 (2021)

The fundamental quasi-normal mode has been observed in several GW events and is compatible with **Kerr black hole remnants**.

Tests of the black hole paradigm

Kerr black holes are determined uniquely by 2 parameters:

- Mass
- Angular momentum

Carter, PRL **26**, 331 (1971); Robinson, PRL **34**, 905 (1975)

A test of the no-hair theorem requires the identification of **at least two quasi-normal modes** in the ringdown.

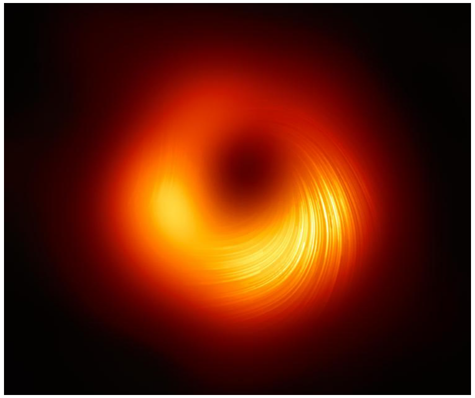
The detection of modes other than the fundamental one is challenging.
Next generation detectors will allow for tests of the black hole paradigm.

Berti+, PRL **117**, 101102 (2016); Bhagwat+, arXiv: 2304.02283 (2023)

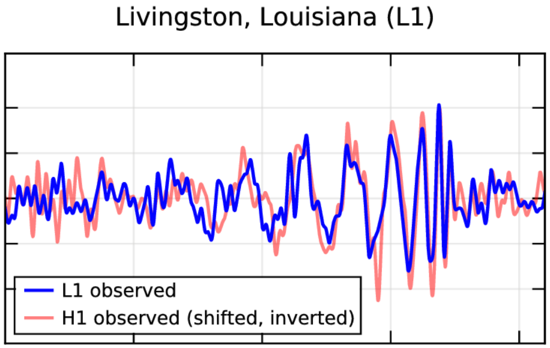
Motivation

Current electromagnetic and gravitational observations are compatible with the **Kerr hypothesis**. *Why do we need further tests?*

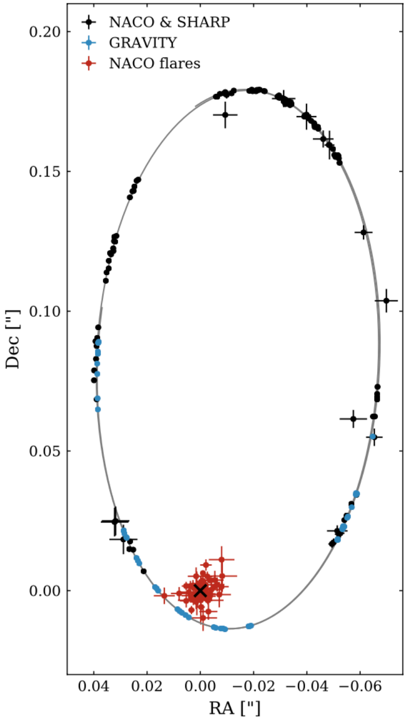
The evidence for black holes is the observation of dark, compact and massive objects.



EHT, ApJL **910**, L12 (2021)

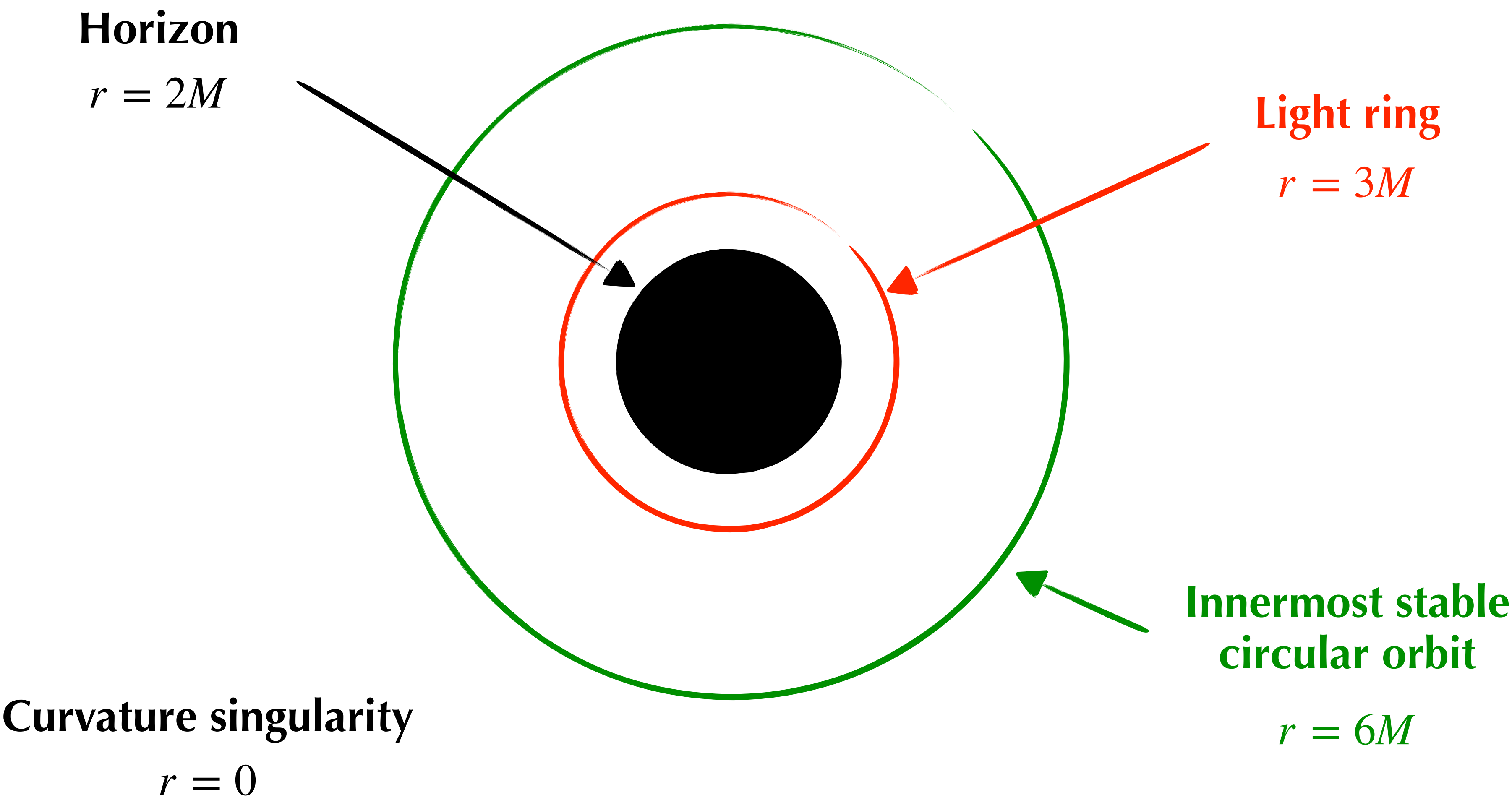


Abbott+, PRL **116** n.6 (2016) 061102



GRAVITY, A&A **636**, L5 (2020)

Black holes in general relativity



Exotic compact objects

New physics can prevent the formation of the horizon:

in quantum-gravity extensions of general relativity (e.g. fuzzballs, gravastars)

Mathur, Fortsch. Phys. **53**, 793-827 (2005); Mazur+, PNAS **101**, 9545-9550 (2004)

in general relativity with dark matter or exotic fields (e.g. boson stars, wormholes)

Liebling+, LRR **20**, 5 (2017); Morris+, Am. J. Phys. **56**, 395-412 (1988)

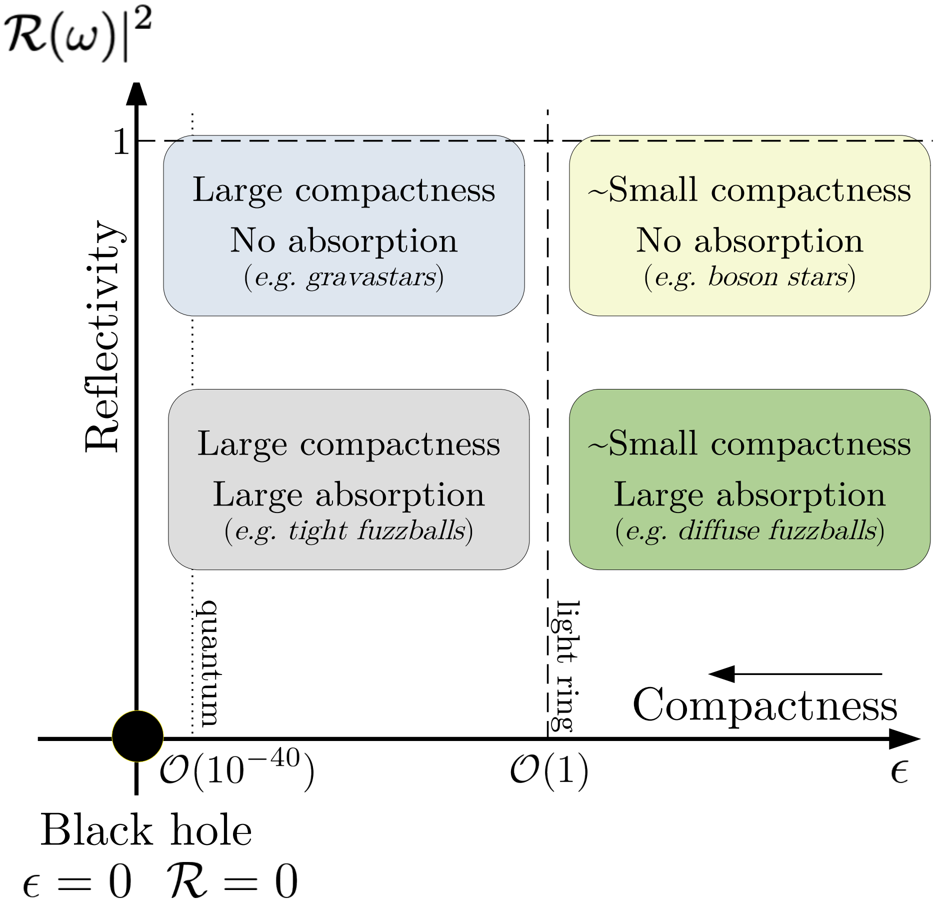
ECOs can mimic black holes and quantify the existence of horizons.

Giudice+, JCAP **10** (2010) 001; Cardoso+, LRR **22**:4 (2019); EM+, Handbook for GW Astronomy, Springer (2021)

A parametrized classification

We analyze a generic model that deviates from a black hole for its:

- **Compactness**
  since the radius of the object is at $r_0 = r_+(1+\epsilon)$
- **Reflectivity**
  that differs from the totally absorbing black hole case



EM, Pani, Raposo, Handbook for GW Astronomy, Springer (2021)

Some questions

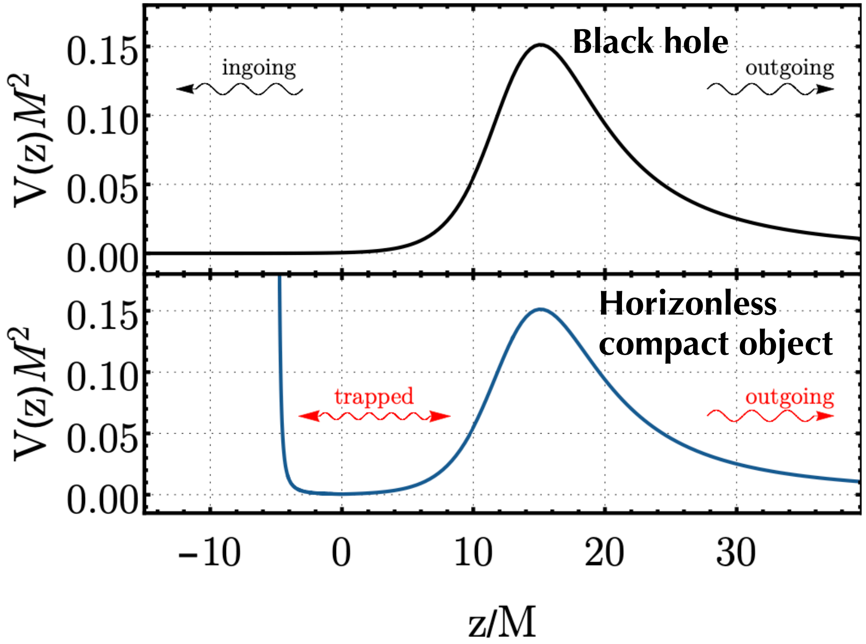
- What are the GW signatures of horizonless compact objects?
- Are horizonless compact objects astrophysically viable?
- Are horizonless compact objects detectable by current and future GW detectors?

Ringdown of horizonless compact objects

The ringdown

The ringdown stage is dominated by the **quasi-normal modes** of the remnant, which describe the response of the compact object to a perturbation.

Cardoso, Pani, LRR **22**:4 (2019)



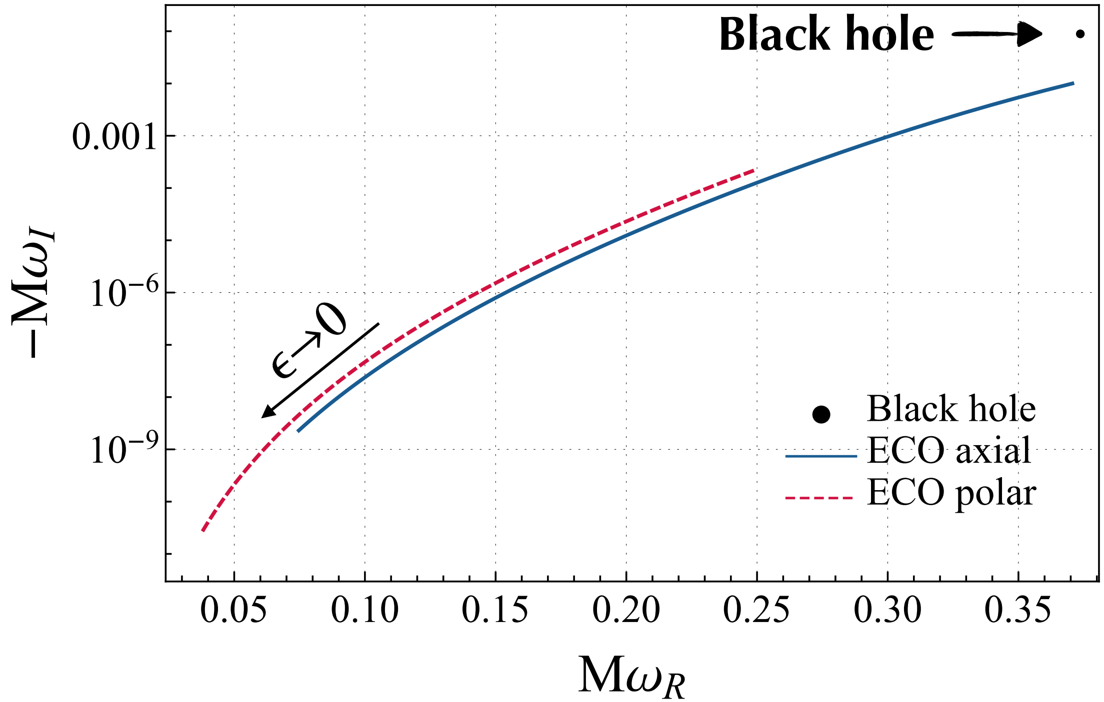
$$\frac{d^2\psi}{dz^2} + \left[\omega^2 - V(z)\right]\psi = 0$$

Teukolsky, Press, ApJ **193** (1974) 443-461

No horizon → Trapped modes → Low- frequency quasi-normal modes

Quasi-normal mode spectrum

Ultracompact object ($\epsilon \ll 1$):



- Axial and polar modes are not isospectral.
- For $\epsilon \to 0$, the quasi-normal modes are low-frequencies and long-lived.

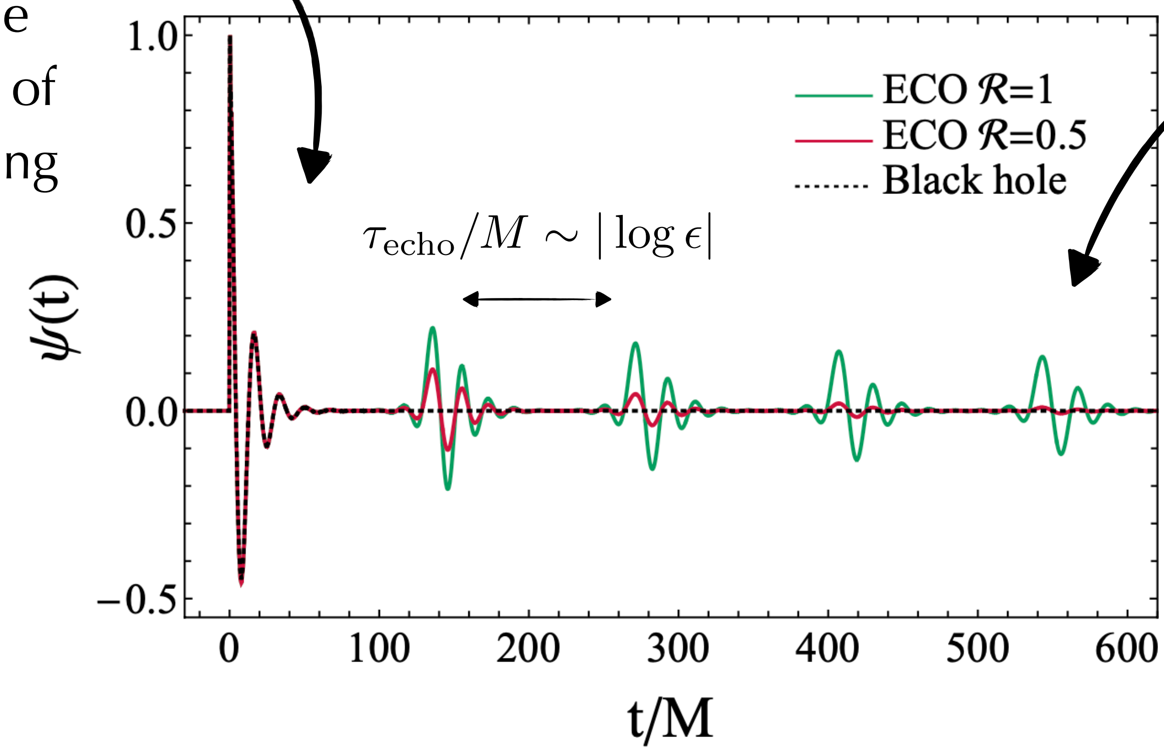
Cardoso+, PRL **116**, 171101 (2016); EM+, Handbook for GW Astronomy (2021)

Ringdown of horizonless objects

Ultracompact object ($\epsilon \ll 1$):

Same prompt ringdown

due to the excitation of the light ring



GW echoes

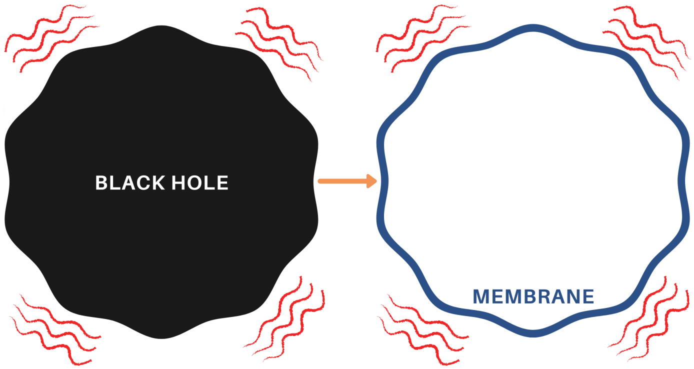
due to trapped modes

Cardoso+, PRL **116**, 171101 (2016); EM+, Handbook for GW Astronomy (2021)

Membrane paradigm

We derive the boundary condition that describes **horizonless compact objects with any compactness** with the membrane paradigm.

EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)

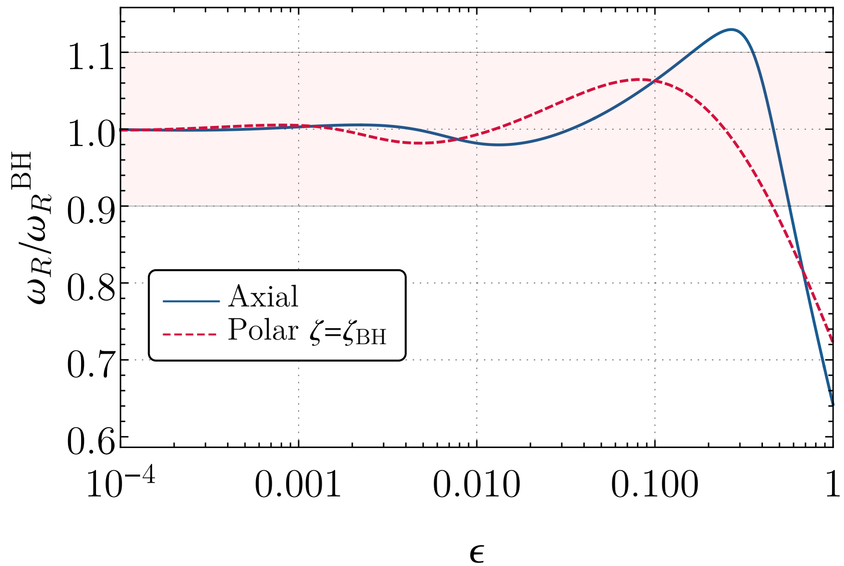


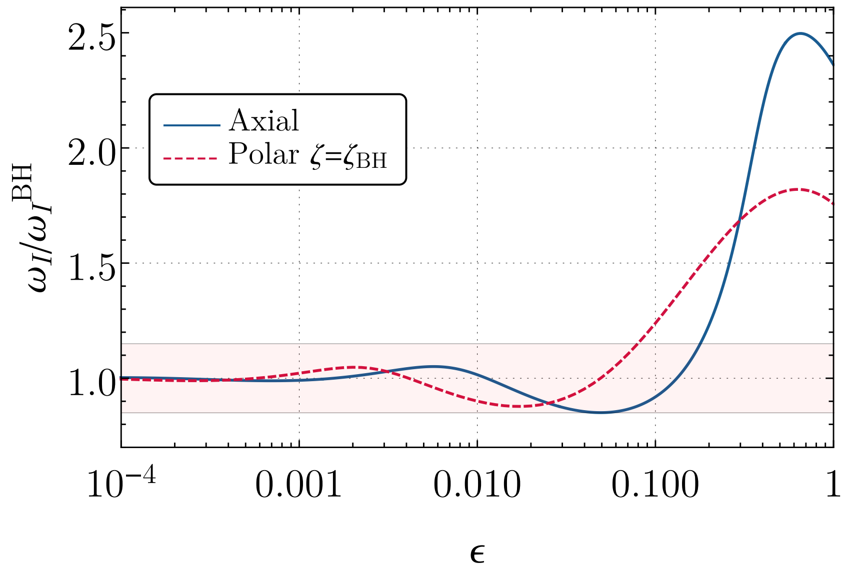
Damour, PRD **18**, 10 (1978); Price, Thorne, PRD **33**, 4 (1986)

A static observer can replace the interior of a perturbed black hole with a fictitious membrane located at the horizon, which is a **viscous fluid** with shear viscosity η and bulk viscosity ζ.

Spectrum of compact objects

Absorbing compact object ($\epsilon \gtrsim 0.01$):





EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)

Horizonless compact objects with $\epsilon \lesssim 0.1$ are compatible with the measurement accuracy of the fundamental quasi-normal mode in GW150914.

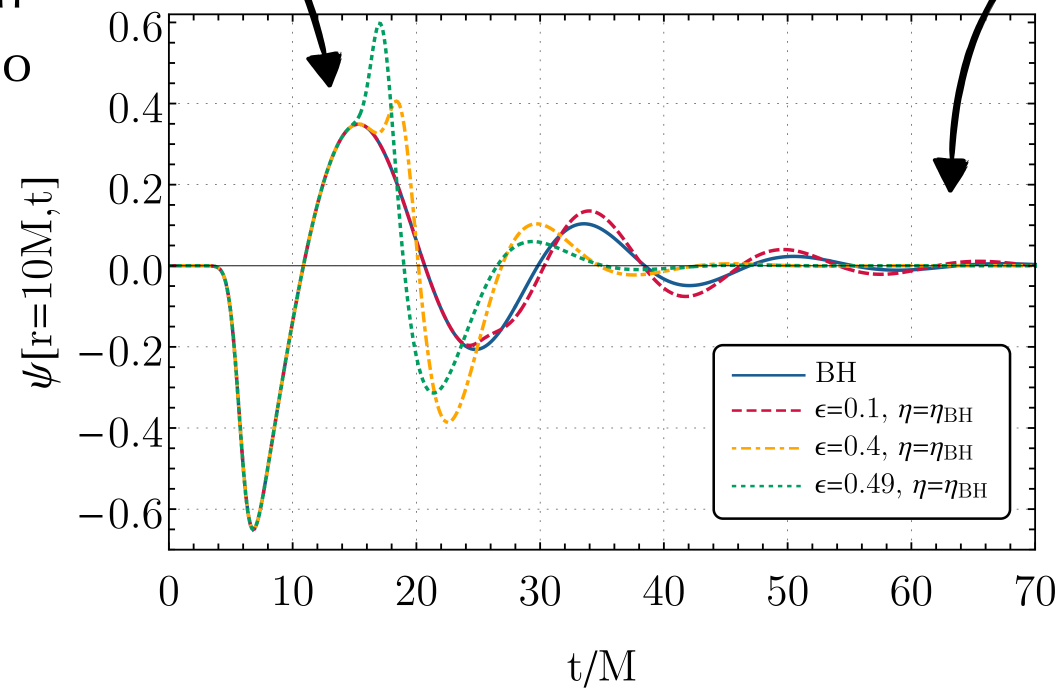
Absorbing compact object ($\epsilon \gtrsim 0.01$):

Modified prompt ringdown

due to the interference with the first GW echo

No subsequent GW echoes

the cavity does not trap efficiently modes

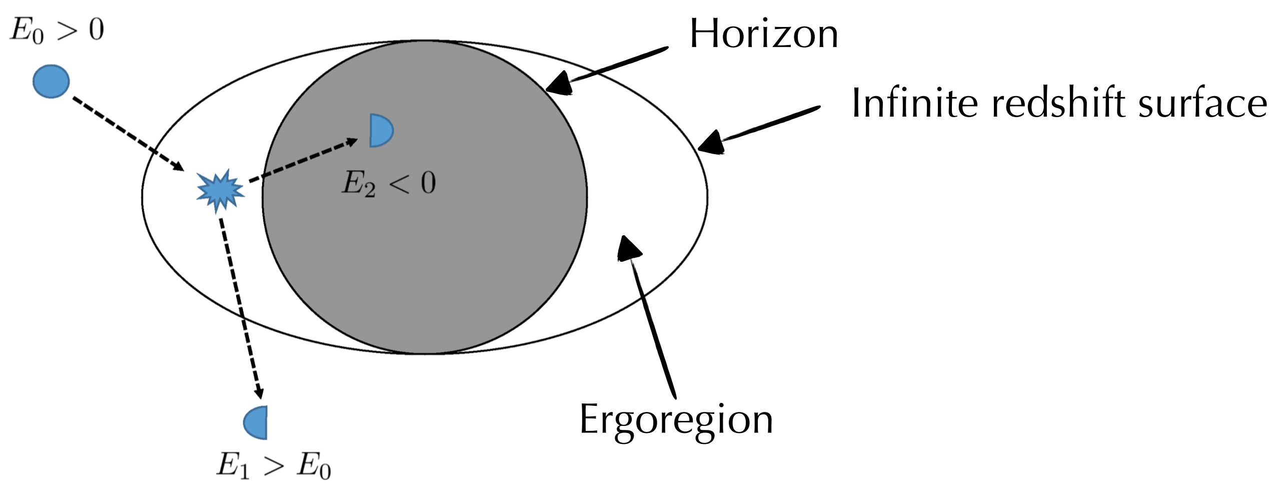


EM, Buoninfante, Mazumdar, Pani, PRD **102**, 064053 (2020)

Astrophysical viability of spinning horizonless compact objects

Ergoregion instability

Spinning compact objects with an ergoregion but without an event horizon might be unstable due to the ergoregion instability.

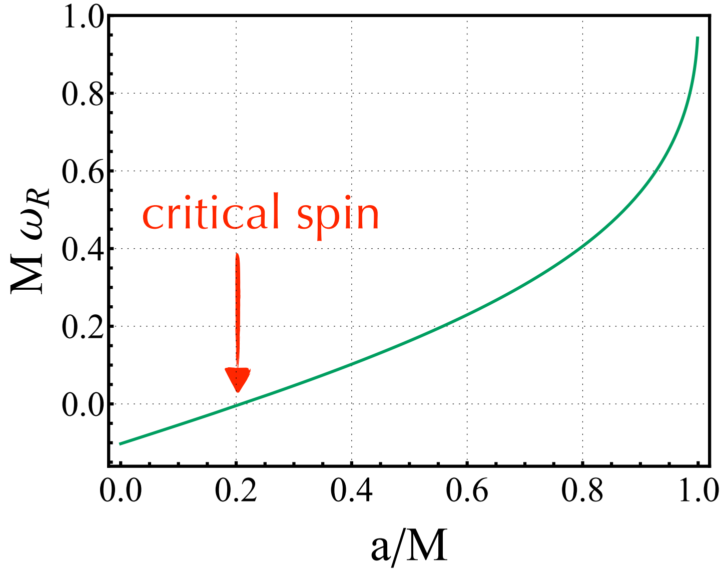


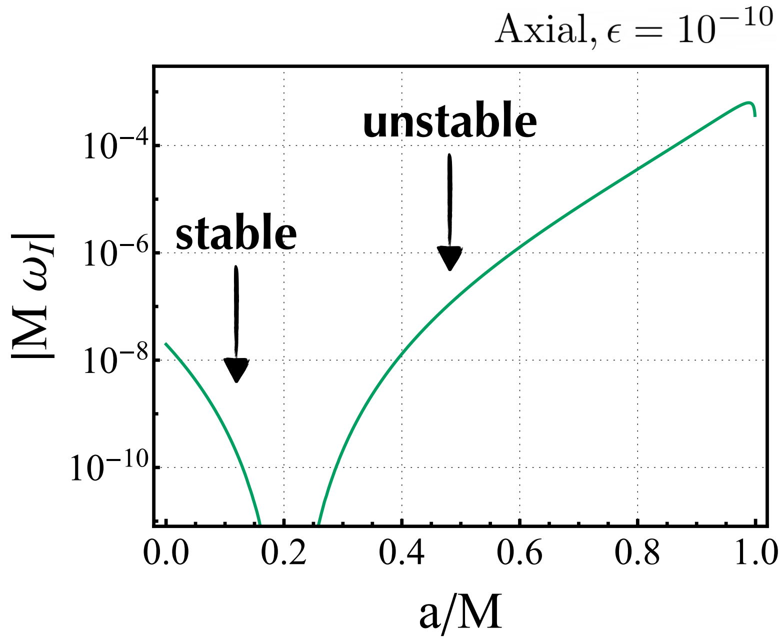
Brito+, Lect. Notes Phys. (2020); Friedman, Commun. Math. Phys. **63**, 243-255 (1978)

If confirmed, the ergoregion instability could provide a strong theoretical argument in favor of the black hole paradigm.

Ergoregion instability

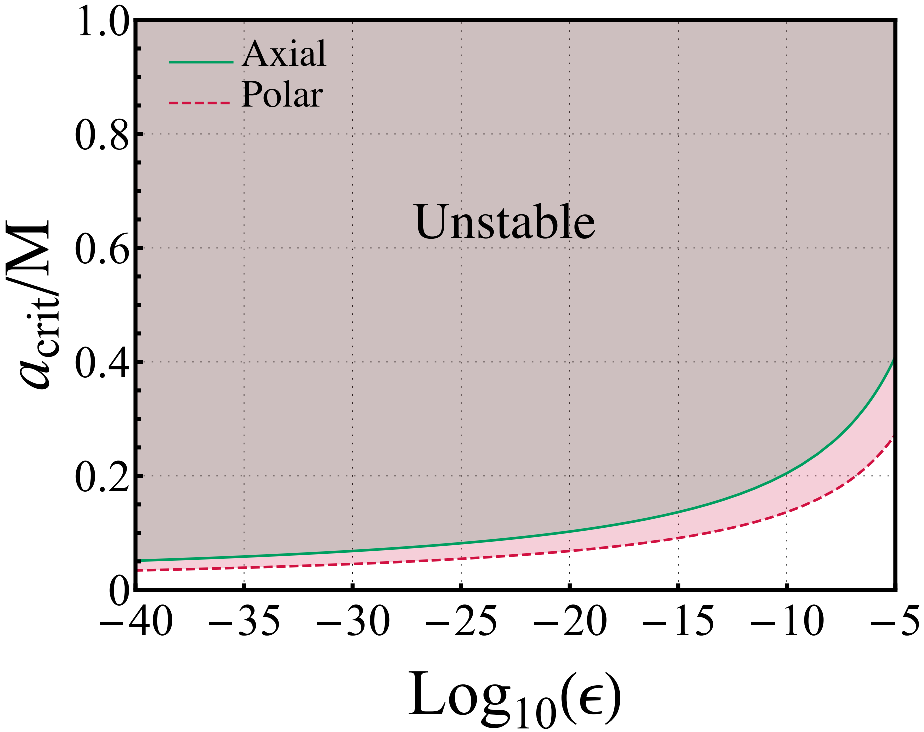
Horizonless compact objects with a **perfectly reflecting surface** are unstable above a critical value of the spin due to the ergoregion instability.





EM, Pani, Ferrari, PRD **96**, 104047 (2017); EM, Cardoso, Dolan, Pani, PRD **99**, 064007 (2019)

Astrophysical impact of the instability



For $\epsilon \to 0$, spinning horizonless compact objects are unstable.

The timescale of instability is short compared to astrophysical timescales:

$$\tau_{\text{instability}} \sim 50 \left(\frac{M}{10 M_\odot}\right) \mathrm{s}$$

EM, Cardoso, Dolan, Pani, PRD **99** (2019) 064007

A putative horizonless compact object with the same spin as that measured for GW150914 would be unstable.

How to quench the ergoregion instability

Partial absorption at the surface makes horizonless compact objects stable.

The minimum absorption rate to quench the instability is the maximum amplification factor of superradiance of black holes.

Spin	**Absorption**
0.7	0.3%
0.9	6%
any	~60%

EM, Cardoso, Dolan, Pani, PRD **99**, 064007 (2019)

Detectability of horizonless compact objects with current and future detectors

Detectability of GW echoes

- A tentative evidence for echoes in LIGO/Virgo data has been reported

  Abedi+, PRD **96**, 082004 (2017); Conklin+, PRD **98**, 044021 (2018); Abedi+, JCAP **11**, 010 (2019)

- Independent searches argued that the statistical significance of echoes is low and consistent with noise

  Westerweck+, PRD **97**, 124037 (2018); Nielsen+, PRD **99**, 104012 (2019); Uchikata+, PRD **100**, 062006 (2019); Lo+, PRD **99**, 084052 (2019); Tsang+, PRD **101**, 064012 (2020)

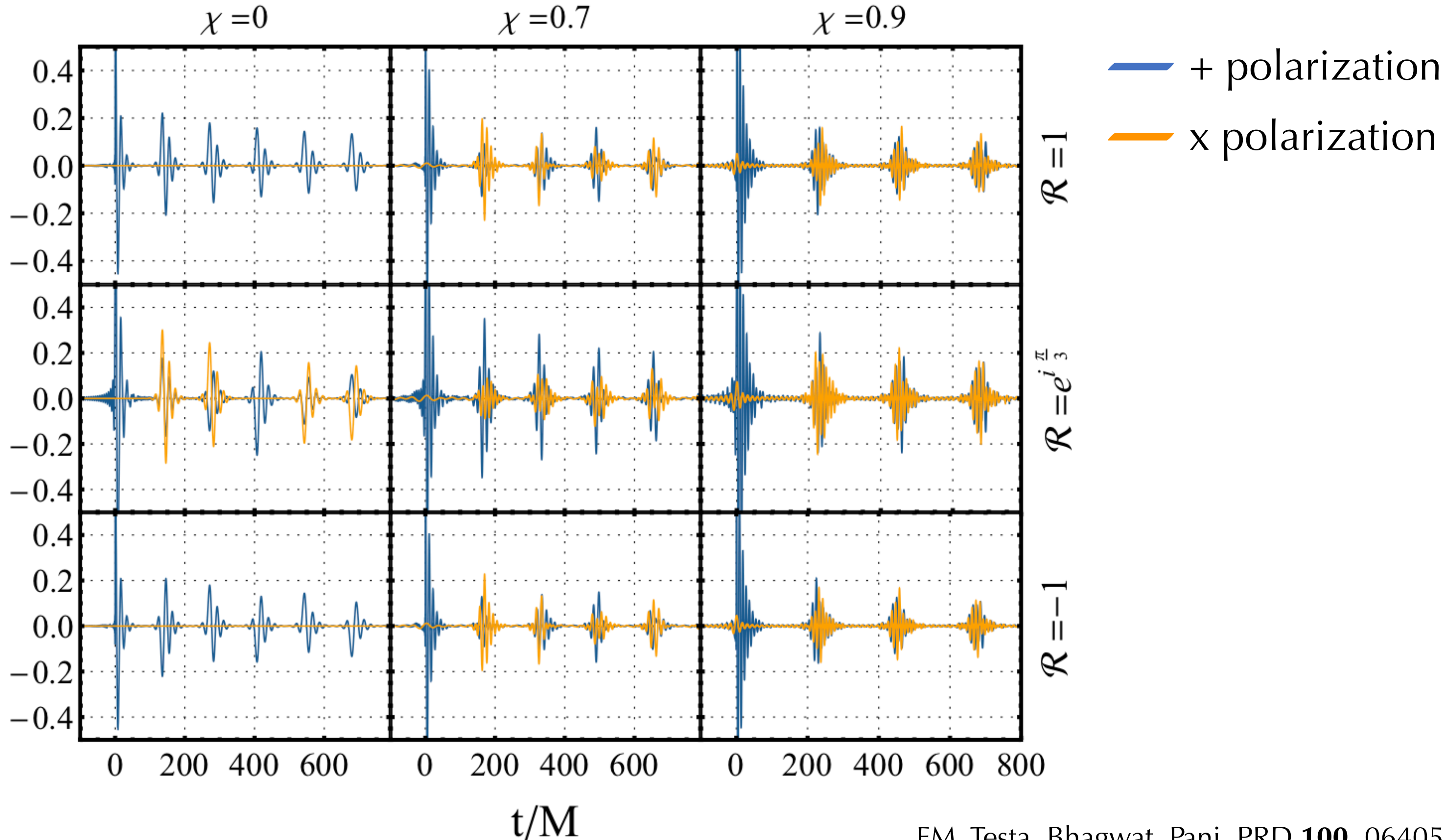
- No evidence for echoes in the third GW observing run

  Abbott+, PRD **103**, 122002 (2021); Abbott+, arXiv: 2112.06861 (2021)

Template for GW echoes

We develop an **analytical low-frequency template** whose parameters are:

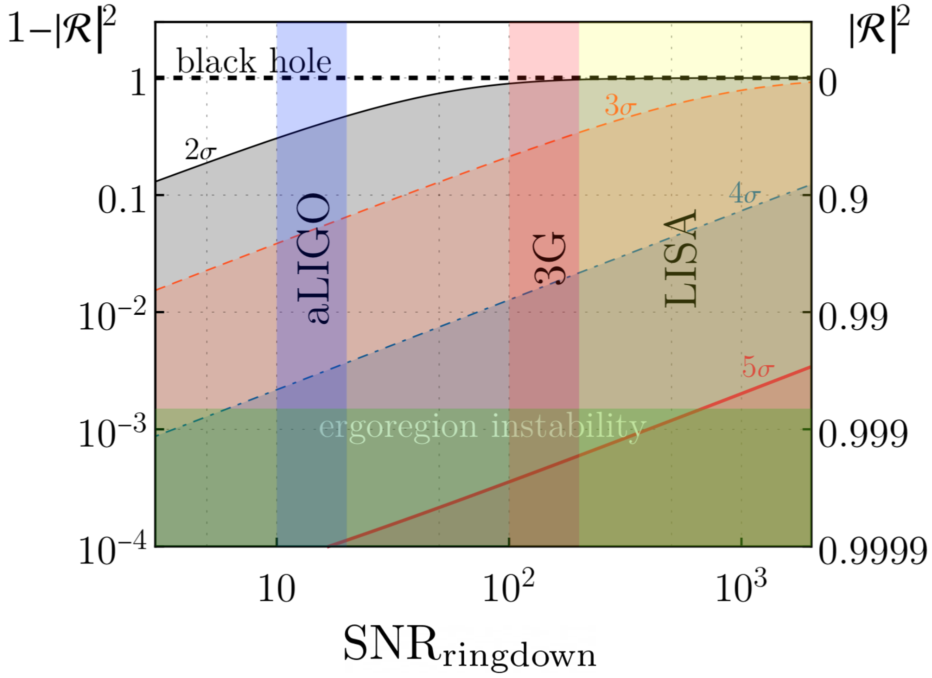
- standard BH ringdown: $M, \chi, A_{+,\times}, \phi_{+,\times}, t_0$
- +2 parameters: $\epsilon, \mathcal{R}(\omega)$



EM, Testa, Bhagwat, Pani, PRD **100**, 064056 (2019)

Prospects with next-generation detectors

With a Fisher analysis we can assess the **detectability of the reflectivity** of compact objects as a function of the signal-to-noise ratio in the ringdown.



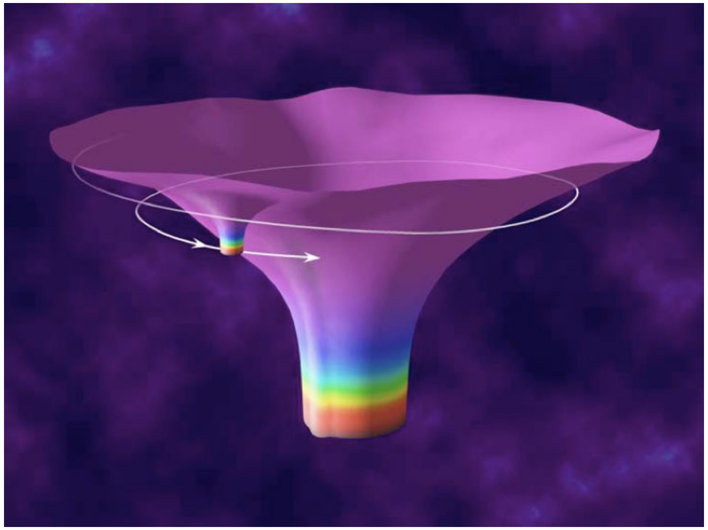
EM, Testa, Bhagwat, Pani, PRD **100**, 064056 (2019)

Excluding or detecting echoes for models with $|\mathcal{R}|^2 < 1$ requires:

$$\mathrm{SNR}_{\mathrm{ringdown}} \gtrsim 100$$

which will be achieved by the Einstein Telescope and LISA.

Extreme mass-ratio inspirals

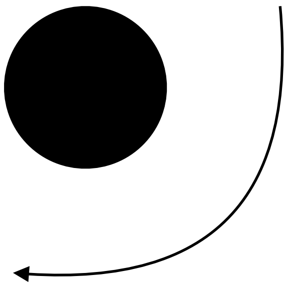


LISA will detect GWs from the inspiral of stellar mass objects around supermassive compact objects at the center of galaxies.

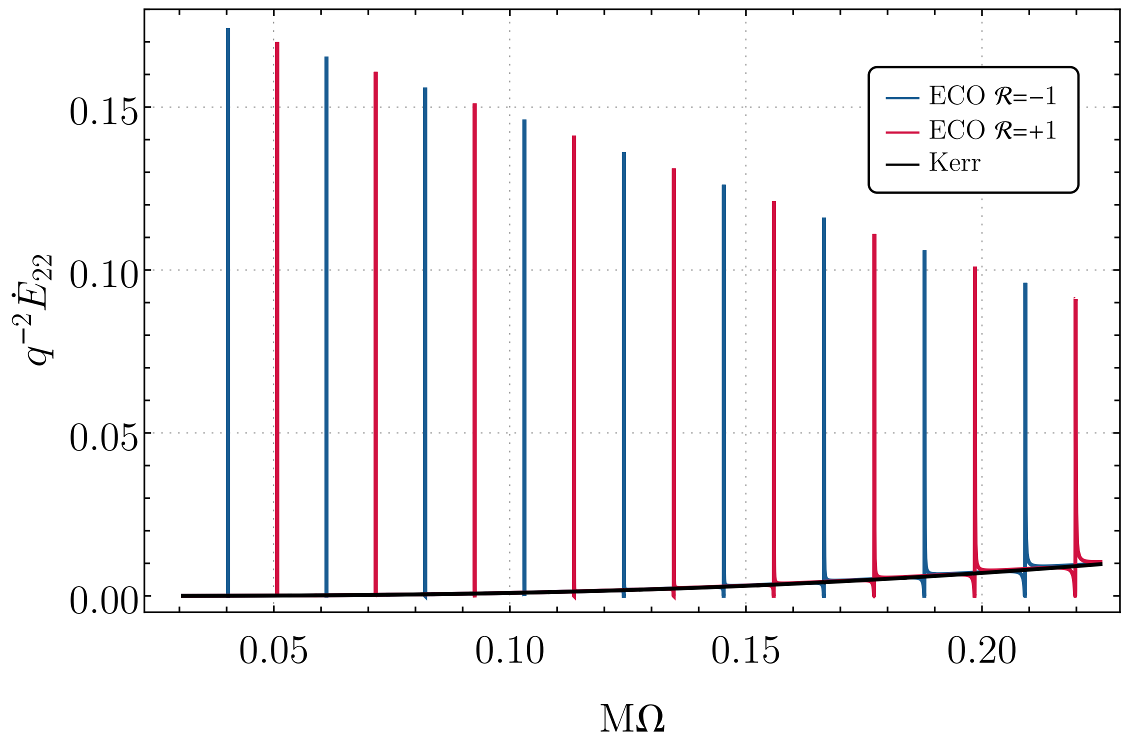
- **Low-frequency resonances** would be excited when the orbital frequency matches the quasi-normal modes of the central ECO.
- Any evidence of **reflectivity** would indicate a departure from the black hole picture.

EM, van de Meent, Pani, PRD **104**, 104026 (2021)

Extreme mass-ratio inspirals



We analyze a point particle in circular equatorial orbits around a spinning horizonless compact object.

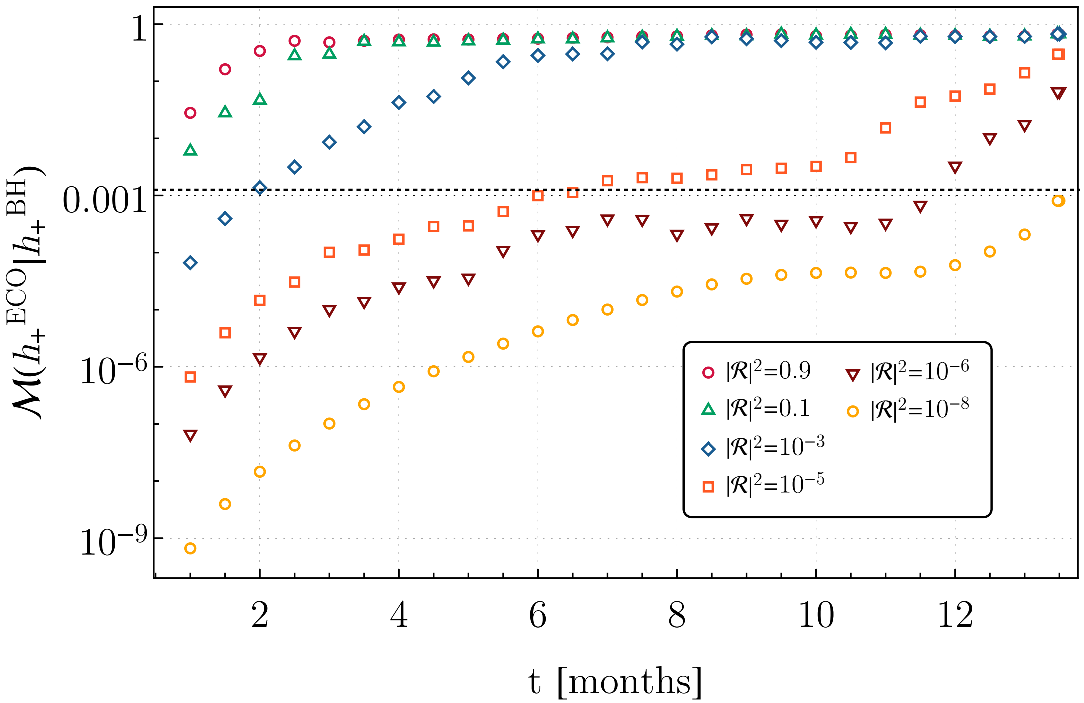


The energy flux is resonantly excited when the orbital frequency matches the quasi-normal modes of the central object.

EM, van de Meent, Pani, PRD **104**, 104026 (2021)

Waveform mismatch

We compute the **mismatch** between the waveforms with a central black hole and a horizonless compact object.



Detectability threshold for LISA

In one year of observation, LISA is sensitive to a reflectivity of the central object $|\mathcal{R}|^2 = \mathcal{O}(10^{-8})$.

EM, van de Meent, Pani, PRD **104**, 104026 (2021)

Conclusions and future prospects

- We can look for new physics at the horizon scale with gravitational waves.
- Horizonless compact objects are not excluded by current observations.
- Next-generation detectors will allow us to perform unprecedented tests of the black hole paradigm.
- Development of a framework to translate parametrized constraints on general relativity to horizonless compact objects.
- Performance of accurate statistical analyses for the detectability of horizonless sources by next-generation detectors.